Journal of the KSTLE Vol. 26, No. 3, June 2010, pp. 175~183
The Korean Society of Tribologists & Lubrication Engineers

The Design Review for Lubrication System of an Internal Combustion Engine

Sang Myung Chun†
Dept. of Automotive Engineering, Hoseo University

내연기관 윤활시스템의 설계검증

전 상 명†
호서대학교 자동차공학과

(Received March 10, 2010; Revised May 2, 2010; Accepted May 10, 2010)

논문초록 – 초기 엔진 개발 단계에서 양질의 엔진 개념 설계를 얻기 위해 가장 중요하게 다루는 분야가 엔진윤활시스템 설계라는 것은 지나친 말이 아니다. 그러므로 초기 개념설계 후 엔진제작에 앞서 초기 설계된 윤활시스템과 그 관련 부품에 대한 시스템 윤활해석을 수행하는 것은 필수적이다. 따라서, 본 논문에서는 초기 개념 설계된 2.0 L DOHC엔진에 대한 엔진 베어링과 윤활시스템에 대하여 수치해석적으로 유로망 해석을 하여 설계검증을 한 결과를 기술하고자 한다.

Abstract – It is not too much to say that, at the beginning of engine development, the most important areas for a good engine concept design is the lubrication system design. So, between right after finishing concept design and before procuring the engine, it is necessary to carry out the system lubrication analysis for the initially designed lubrication system and the related lubricating parts. Therefore, in this paper, it is to describe the results of a design review carried out the numerical net work analysis on the engine bearings and the lubrication system of an initially designed 2.0 L DOHC engine.

Keywords – 엔진윤활시스템(engine lubrication system), 유로망해석(network analysis), 유량(flow rate), 압력감소(pressure drop), 원심입력(centrifugal pressure), 베어링최소유막두께(bearing minimum film thickness), 개념설계(concept design)

1. Introduction

The quality of engine lubrication is depends upon how much oil is supplied and how the lubricant is fed under pressure to the lubricated components. This state of lubrication is closely related with the safe operation of an engine and the lifetime. Specially, in the concept design stage of an engine, the experimental verification of the engine lubrication system can not be performed. Therefore, a practically optimized analytical method has been required by engine designers. Some methods have been developed by several researchers[1-10].

In this paper, the general flow network theory and the flow characteristics of each lubricated component are used as proposed by Chun[9,10]. The flow characteristics are systematically structured in order to analytically simulate the flow network of engine lubrication system. In the analysis, the various design guidelines are applied.

Here, for example, it is to be investigated the lubrication system of a newly designed 2.0 DOHC gasoline engine by numerical analyses. To do this, all the dimensions measured at room temperature are used.

†주저자・책임저자 : smchun@hoseo.edu

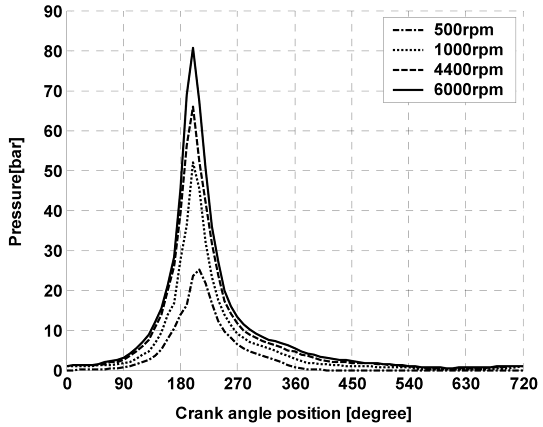


Fig. 1. Virtual combustion pressure distributions for the expected performance of 2.0 L DOHC Gasoline Engine.

The combustion chamber pressures and temperatures of engine oil and the related parts, are used those of other engines similar to the expected performance of the 2.0 L DOHC gasoline Engine.

First, to carry out the numerical analysis of engine bearings, a computer program developed by Chun[11] based on the lubrication theory of dynamically loaded journal bearings, is used. Then, to perform the analysis of engine lubrication system, another computer program also developed by Chun[9,10] based on the theory of flow network analysis together with bearing lubrication theory, is used. The programs had already verified as using them for other engine development projects [9,10].

The work scopes of this study are;

1) Numerical analysis of engine bearing oil film thickness
   a) To calculate minimum oil film thickness of a big-end bearing.
   b) To calculate minimum oil film thickness of a main bearing.
2) Numerical analysis of engine lubrication system
   a) To calculate pressure and flow rate at key positions inside the flow net work of engine lubrication system.
   b) To find places required more pressure inside the flow network.
   c) To verify whether the performance of engine oil pump is enough or not.

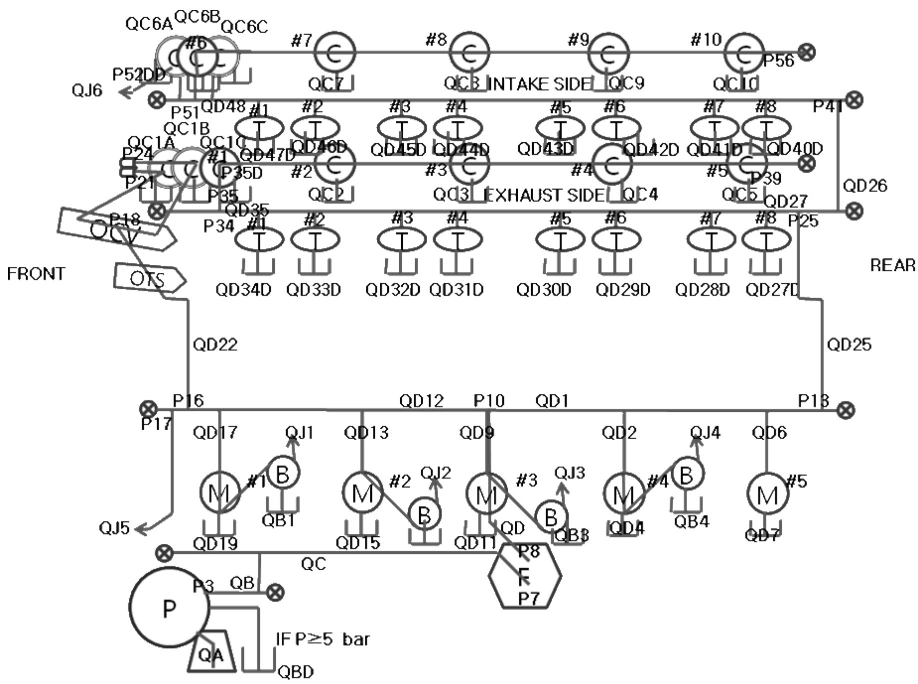
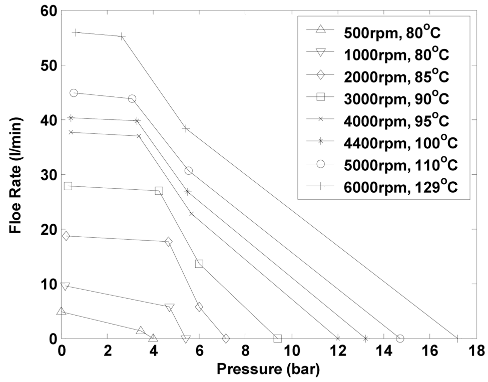
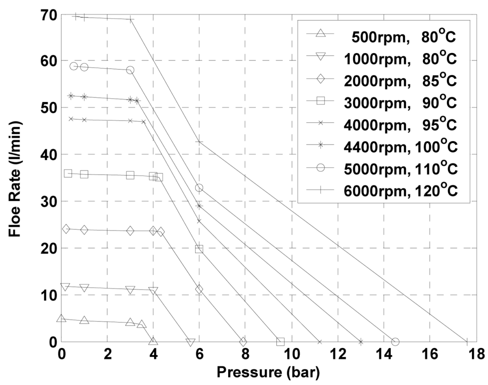


Fig. 2. A schematic diagram of 2.0 DOHC engine lubrication system.



(a) Pressure-flow rate curve of oil pump for a current 1.6 DOHC gasoline engine



(b) Pressure-flow rate curve of the newly designed oil pump for a 2.0 DOHC gasoline engine

Fig. 3. The flow characteristics of oil pumps.

2. Engine Lubrication System

The engine involved for this study is a 4 cylinder 2.0 L DOHC gasoline engine with the expected combustion pressure distributions as shown on Fig. 1.

The lubrication system as shown in Fig. 2 is composed of oil pan, suction pipe, oil pump(P), oil filter(F), main bearings(M #1 - M #5), connecting rod bearings (B #1 - B #4), oil jets on each big end of connecting rod(QJ1 - QJ4), cam bearings(C #1 - C #10), hydraulic tappets(T #1 - T #8) for both intake and exhaust side, oil jets for chain timing drive system(QJ5, QJ6), oil control valve(OCV) for variable valve timing system, oil temperature sensor(OTS), oil drilling holes in the crank shaft web and cam shaft, and horizontal and vertical oil galleries. The lubricant is sucked by the oil pump from the oil pan through a suction pipe with strainer welded at the front. Then, the lubricant passes through an oil filter, and is distributed to main and big end bearings, and continues to flow to jets on connecting rod. At the front end of main oil gallery on cylinder block, there are two branches of the gallery. One turns vertically toward the front of exhaust cam shaft at cylinder head through the oil control valve. Other turns down to the oil jet for the lower part lubrication of a chain drive system. At the rear end of main oil gallery on cylinder block, one branch of the oil gallery turns vertically toward the rear end of exhaust cam shaft at cylinder head for the lubrication of all tappets and cam bearings located both exhaust and intake sides as shown in Fig. 2. Finally, the lubricant passed through valve train at cylinder head drains vertically down through several oil drillings to the oil pan.

Here, Points P3, P8, P10, P13, P17, P18, P21, P24, P25, P34, P39, P41, P51, P52DD, P56 are some important node points for checking oil pressure inside oil galleries.

In this paper, two oil pump's performance curves are used for the evaluation of the initially designed lubrication system. One is the pressure-flow rate curve of the oil pump for a current 1.6 DOHC gasoline engine as shown in Fig. 3(a). The other is the newly designed one for a 2.0 DOHC gasoline engine as shown in Fig. 3(b).

3. System Analysis

In general, under a certain velocity, the flow rate of oil inside pipes increases as the oil pressure increases. Therefore, the higher the discharging pressure of oil pump is, the more the oil is needed. On the other hand, the flow rate of oil pump is inversely proportional to the discharging pressure. To satisfy the flow rate needed by an engine, the flow rate from oil pump is equal to the total flow rate needed by each lubricated components of an engine.

Therefore, as the first step to solve the whole system of flow network, the flow rate of suction by oil pump is assumed. The discharge flow rate is calculated using the measured volumetric efficiency of oil pump. Then,

Table 1. The calculated design parameters for big-end and main bearing clearances, 0.040 and 0.052 mm

@ 6000 rpm, WOT	Big-end bearing	Main bearing #1	Main bearing #2	Main bearing #3	Main bearing #4	Main bearing #5
Max. load (N)	25,420	14,062	22,195	16,204	22,324	14,018
Max. Specific load (MPa)	29.42	7.13	11.26	8.22	11.32	7.11
Max. film press. (MPa)	134.6	18.8	44.8	34.1	45.1	18.9
Power loss (W)	830	627	400	809	399	627
Max. eccen.	0.9562	0.8407	0.8282	0.8904	0.8283	0.8410
Min. film thick. (μm)	0.88	4.14	4.47	2.85	4.46	4.13
Recommended min. film thickness(μm) @ rated speed						
Guide Line	>0.7	>0.50	>0.50	>0.50	>0.50	>0.50

Table 2. The calculated design parameters for big-end and main bearing clearances, 0.054 & 0.070 mm and 0.034 & 0.050 mm

@ 6000 rpm, WOT	Big-end bearing	Main bearing #1	Main bearing #2	Main bearing #3	Main bearing #4	Main bearing #5
Max. load (N)	25,420	14,062	22.195	16,204	22,324	14,018
Max. Specific load (MPa)	29.42	7.13	11.26	8.22	11.32	7.11
Max. film press. (MPa)	121.9/165.3	18.7/20.2	44.1/51.2	33.4/40.9	44.4/51.5	18.8/20.3
Power loss (W)	833/825	625/655	405/358	805/837	404/358	624/654
Max. eccen.	0.9440/0.9739	0.8323/0.8941	0.8212/0.8762	0.8844/0.9286	0.8213/0.8761	0.8325/0.8943
Min. film thick. (μm)	0.95/0.70	4.19/3.71	4.47/4.33	2.89/2.50	4.47/4.34	4.19/3.70
Recommended min. film thickness(μm) @ rated speed						
Guide Line	>0.7	>0.50	>0.50	>0.50	>0.50	>0.50

the discharge pressure is determined by the flow characteristic curves of the oil pump. Further, it is calculated the pressure drop through each passage and the consumed oil flow rate by each lubricated parts. The consumed flow rate is checked whether it is in the same range of the assumed discharge flow rate or not. If the results were not satisfied within a certain range of error, the procedure is to be iterated with a better-adjusted value of the discharge flow rate till the value is satisfied. Finally, the discharge flow rate is decided, and the pressure and flow distribution at every points and components can be obtained.

4. Computer Program

The computer program is composed of a main program and several subprograms. In the main program, all the data of lubrication system are recorded. Those are the physical geometry of the related components and the experiment data of engine and components, for example, the flow characteristics of oil pump and oil filter. And the network frame of lubrication system is organized. The whole network is divided into several small networks, for examples, the bearing group 1 to 4 for each set composed of a main bearing, a big-end bearing and a oil jet, the bearing group 5 for rear main bearing only, the hydraulic tappet group 1 and 2 for each intake side and exhaust side, and the cam bearing group 1 and 2 for each intake side and exhaust side. The involved subprograms are of the calculation of basic equations for pipe flow, oil pump flow, oil filter flow, bearing flow including bearing load, effective temperature, eccentricity and power loss calculation with pressure data of combustion chamber, centrifugal

Table 3. Pressures and flow rates at some important points of 2.0 L engine lubrication system with new oil pump

Positions calculated pressures	Pressure (bar)		Positions calculated flow rates	Flow Rate (cc/sec)	
	500(1000) rpm	6000 rpm		500 rpm	6000 rpm
Oil pump exit	4.575 (4.950)	4.950 (valve open)	For crank shaft bearing and oil jet	16.68	77.53
After through oil filter	4.386	4.797	For tappets at exhaust side	5.08	34.17
Mid-position of main oil gallery	4.373	4.775	For cam bearings at exhaust side	2.34	6.82
Front end of main oil gallery	4.373	4.775	For tappets at intake side	5.08	34.14
Rear end if main oil gallery	4.372	4.769	For cam bearings at intake side	7.44	23.88
Entrance of OCV	4.351	4.752	For Top oil jet for chain	5.33	6.27
Drain pressure at the front of Exh. Cam shaft	4.346	4.653	For Bottom oil jet for chain	5.37	6.34
Rear side of Cylinder Head before Exh. Tappets	4.348	4.713	Drain flow at the front of Exh. Cam Shaft	1.38	5.35
Front side of Cylinder Head after Exh. Tappets (Exh. Cam Shaft Entrance)	4.348	4.709	Drain flow from Exh. Cam Bearing #1 a or b	1.80	6.05
Rear side of Exh. Cam Shaft	4.343	4.614	Front vertical oil gallery	3.18	11.4
Rear side of Cylinder Head before Int. Tappets	4.347	4.702	Rear vertical oil gallery	25.27	105.28
Front side of Cylinder Head after Int. Tappets (Int. Cam Shaft Entrance)	4.346	4.694	Discharge flow rate from oil pump	50.50	200.55
Front Oil Jet at Int. Cam Shaft	4.343	4.689	Total Oil Suction	71.0	479.0
Rear side of Int. Cam Shaft	4.341	4.596	Pump Leakage/ Relief Valve By-Pass (Vol. Eff.)	20.50 0.0 (71.1%)	169.76 108.69 (41.9%)

pressure of rotating parts, oil jet flow, hydraulic tappet flow, and the expression of density and viscosity depending on temperature. During calculation, a certain assumed flow rate for each group is forced to converge by iteration. If the iteration were successfully performed for the whole lubrication system, then all the calculated data are written on the output files.

5. Results

5-1. Numerical Analysis of Engine Bearing Oil Film Thickness

The initially designed engine has the clearance of big-end bearings as 0.040~0.090mm, and the one of main bearings as 0.052~0.096. Here, it is going to be investigated whether these clearances are safe or not.

First, the recommended minimum oil film thickness as a design guide line is compared with the calculated minimum oil film thickness for the case with the lower bound of bearing clearances, i.e. the big-end bearing clearance, 0.040 mm and main bearing clearance, 0.052 mm. The minimum oil film thickness turns out to be 0.88 μm that is satisfied with the design guide line as shown on Table 1.

Further, it is to investigate for the two cases with the big-end and main bearing clearance, 0.054 &

Table 4. Suction speed and pressure at oil bores of 2.0L engine lubrication system with new oil pump

Engine Speed (rpm)	500 rpm	6000 rpm
Suction Speed (cm/sec) (Recom. value: < 300)	17.86	120.47
Saturation Pressure (bar) at C/S Oil Bore / Min. Pressure (bar) at C/S oil bore	-0.628 bar @ 3.351 air volume % (Supposed max. value) / 4.348(#1), 4.353(#2), 4.353(#3), 4.347(#4)	-0.628 bar @ 3.351 air volume % (Supposed max. value) / 3.548(#1), 3.556(#2), 3.559(#3), 3.536(#4)
Crank Oil Bore #1 Pressure (bar)/ Centrifugal Resistance Pressure (bar)	4.380/0.00895	4.7793/1.2495
Crank Oil Bore #2 Pressure (bar)/ Centrifugal Resistance Pressure (bar)	4.381/0.00895	4.7814/1.2495
Crank Oil Bore #3 Pressure (bar)/ Centrifugal Resistance Pressure (bar)	4.380/0.00895	4.7814/1.2495
Crank Oil Bore #4 Pressure (bar)/ Centrifugal Resistance Pressure (bar)	4.380/0.00895	4.7809/1.2495
Exhaust Cam #5 Oil Bore Pressure (bar)/ Centrifugal Resistance Pressure (bar)	4.345/0.001896	4.7059/0.09211
Intake Cam #5 Oil Bore Pressure (bar)/ Centrifugal Resistance Pressure (bar)	4.343/0.001897	4.6879/0.09211

0.070 mm(more safe case), and 0.034 and 0.050 mm (more severe case), the minimum oil film thickness for both cases are respectively 0.95 and 0.70 μm that are also satisfied with the design guide line as shown on Table 2.

Therefore, the big-end bearing diameter clearance is recommended as 0.034~0.054 mm. So the initially designed big-end bearing clearance is desirable to be reduced a little as the recommended one in order to get more load carrying capacity owing to increasing pressure. And the initially designed value for the main bearing diameter clearance, 0.052~0.096 mm, is safe enough.

6-2. Numerical Analysis of Engine Lubrication System

For the numerical analysis of the initially designed 2.0 L gasoline engine lubrication system, two oil pumps are tried to analysis. One is an oil pump with the maximum flow rate as 57 l/min @ 6000 rpm currently being applied a 1.6L DOHC gasoline engine. The other is a new oil pump with the maximum flow rate as 70 l/mim @ 6000 rpm. It is newly modified and curve-fitted based on the oil pump performance of the 1.6L gasoline engine. These two oil pump's performance curves are shown in Fig. 3.

In addition, the relief valve on oil pump is to be opened at 5bar. Then the discharge pressure drop a little. Here, it is set at 0.05 bar less than 5.0 bar. For the dimension of gallery, a special investigation is required at the rear vertical gallery where the cross section reduces too much from cylinder block side to cylinder head side. In details, referring to Fig. 2, the cross section area of the vertical gallery at cylinder block is 0.636×10^{-4} m^2 (dia. 0.9×10^{-2} m). The cross section of horizontal oil feed surge on cylinder head is 1.463×10^{-4} m^2 (the corresponding. dia. 1.365×10^{-2}). The cross section area of the vertical gallery at cylinder head is 0.196×10^{-4} m^2 (dia. 0.5×10^{-2} m).

As the results of the calculation of numerical network analysis, it was found as follows:

First of all, the diameter of a rear vertical oil gallery at cylinder head is supposed to change from original dimension, 5 mm to new recommended dimension, 7 mm. Under 5 mm, the flow resistance at the entrance is too much. So the big pressure drop was occurred. So, all the simulations were carried out with 7 mm diameter.

Under operation with the current oil pump, the relief valve may be not opened up to 1000 rpm as shown on Table 5. But, at 1000 rpm, it is very sensitive to the temperature operating condition. So, if the temperature were below 80°C, the valve could be opened. Then, it can be dangerous because the oil pump discharge flow rate can be drastically reduced.

Table 5. Pressures and flow rates at some important points of 2.0 L engine lubrication system with current oil pump for 1.6 L engine

Positions calculated pressures	Pressure (bar)		Positions calculated flow rates	Flow Rate (cc/sec)	
	500 (1000) rpm	6000 rpm		500 rpm	6000 rpm
Oil pump exit	3.426 (4.999)	4.950 (valve open)	For crank shaft bearing and oil jet	12.82	77.58
After through oil filter	3.273	4.799	For tappets at exhaust side	4.15	34.17
Mid-position of main oil gallery	3.260	4.777	For cam bearings at exhaust side	1.57	7.27
Front end of main oil gallery	3.260	4.477	For tappets at intake side	4.15	34.15
Rear end if main oil gallery	3.259	4.472	For cam bearings at intake side	5.39	22.06
Entrance of OCV	3.239	4.754	For Top oil jet for chain	4.48	6.27
Drain pressure at the front of Exh. Cam shaft	3.233	4.656	For Bottom oil jet for chain	4.52	6.34
Rear side of Cylinder Head before Exh. Tappets	3.236	4.716	Drain flow at the front of Exh. Cam Shaft	0.84	4.24
Front side of Cylinder Head after Exh. Tappets (Exh. Cam Shaft Entrance)	3.236	4.712	Drain flow from Exh. Cam Bearing #1 a or b	1.20	6.06
Rear side of Exh. Cam Shaft	3.231	4.617	Front vertical oil gallery	2.04	10.30
Rear side of Cylinder Head before Int. Tappets	3.235	4.706	Rear vertical oil gallery	19.74	103.92
Front side of Cylinder Head after Int. Tappets (Int. Cam Shaft Entrance)	3.235	4.698	Discharge flow rate from oil pump	39.12	198.14
Front Oil Jet at Int. Cam Shaft	3.232	4.693	Total Oil Suction	55.0	469.0
Rear side of Int. Cam Shaft	3.230 (Min.)	4.600 (Min.)	Pump Leakage/ Relief Valve By-Pass (Vol. Eff.)	15.88 0.0 (71.1%)	166.21 104.65 (42.2%)

Meanwhile, under operation with the new oil pump, the valve was opened at 1000 rpm as shown on Table 3. But the discharge flow was enough amounts.

Consequently, if the flow characteristics at 1000 rpm of the oil pump installed at the 1.6 L engine could be improved with a flatter curve, instead of slope curve, of flow rate up to 4.7 bar, the oil pump installed at the 1.6 L engine could be applied to new 2.0 L DOHC engine.

As shown in Table 3, under operation with the new oil pump at 6000 rpm, the maximum oil pressure at pump exit is about 4.95 bar because of the relief valve open. The minimum pressure is about 4.596 bar at the rear end of intake cam oil bore. At 500 rpm, the oil pressure at pump exit is 4.575 bar at the closing state of the relief valve. The pressure at the rear end of intake cam oil bore is 4.341 bar.

As shown in Table4, the suction speeds at every rpm are reasonable to most of engine speeds as comparing to the recommended speed. The centrifugal resistant pressure dose not prevents the inlet oil at the entrance of crankshaft oil bore. Also the saturation pressure for the entrained air bubble, in which the supposed maximum air volume in oil at rated speed is about 3%, is lower enough comparing to the minimum pressures of

Table 6. Suction speed and pressure at oil bores of 2.0 L engine lubrication system with current oil pump for 1.6 L engine

Engine Speed (rpm)	500 rpm	6000 rpm
Suction Speed (cm/sec) (Recom. value: < 300)	13.83	117.96
Saturation Pressure (bar) at C/S Oil Bore / Min. Pressure (bar) at C/S Oil bore	-0.628 bar @ 3.351 air volume % (Supposed max. value) / 3.487(#1), 3.492(#2), 3.492(#3), 3.487(#4)	-0.628 bar @ 3.351 air volume % (Supposed max. value) / 3.553(#1), 3.561(#2), 3.564(#3), 3.542(#4)
Crank Oil Bore #1 Pressure (bar)/ Centrifugal Resistance Pressure (bar)	3.267/0.00895	4.7830/1.2495
Crank Oil Bore #2 Pressure (bar)/ Centrifugal Resistance Pressure (bar)	3.268/0.00895	4.7835/1.2495
Crank Oil Bore #3 Pressure (bar)/ Centrifugal Resistance Pressure (bar)	3.268/0.00895	4.7834/1.2495
Crank Oil Bore #4 Pressure (bar)/ Centrifugal Resistance Pressure (bar)	3.267/0.00895	4.7814/1.2495
Exhaust Cam #5 Oil Bore Pressure (bar)/ Centrifugal Resistance Pressure (bar)	3.233/0.001896	4.7090/0.09211
Intake Cam #5 Oil Bore Pressure (bar)/ Centrifugal Resistance Pressure (bar)	3.232/0.001897	4.6918/0.09211

crank shaft oil bores.

As shown in Table 5, under operating with the current oil pump, at 6000 rpm, the max oil pressure at pump exit is also about 4.95 bar because of opening the relief valve. The minimum pressure at the left end of intake cam oil bore is 4.601 bar. At 500 rpm, the relief valve is not opened. The oil pressure at pump exit is 3.426 bar at the closing state of the relief valve. The pressure at the rear end of intake cam oil bore is 3.230 bar.

As shown in Table 6, he suction speeds at every rpm are reasonable as comparing to the recommended speed. The centrifugal resistant pressure dose not prevents the inlet oil at the entrance of crankshaft oil bore. Also the saturation pressure for the entrained air bubble, in which the supposed maximum air volume in oil at rated speed is about 3%, is lower enough comparing to the minimum pressures of crank shaft oil bores.

6. Conclusions

1) Numerical Analysis of Engine Bearing Oil Film Thickness

a) The initially designed clearance (0.052~ 0.096 mm) of main bearings is acceptable. However, that (0.040~0.090 mm) of big-end bearings is required to adjust. The value of recommended big-end clearance is recommended between 0.034~0.054 mm.

2) Numerical Analysis of Engine Lubrication System

a) The diameter of a rear vertical oil gallery at cylinder head is supposed to change from 5 mm to 7 mm.

b) If the flow characteristics at 1000 rpm of the oil pump installed at 1.6 DOHC engine could be improved to a flatter curve of flow rate up to 4.7 bar, the oil pump installed at 1.6 DOHC engine could be applied to 2.0 DOHC engine.

c) Under operation with the new oil pump at 6000 rpm, the maximum oil pressure at pump exit is about 4.95 bar because of the relief valve open. The minimum pressure is about 4.596 bar at the rear end of intake cam oil bore. At 500 rpm, the oil pressure at pump exit is 4.575 bar at the closing state of the relief valve. The pressure at the rear end of intake cam oil bore is 4.341 bar.

d) Under operating with the current oil pump, at 6000 rpm, the max oil pressure at pump exit is also about 4.95 bar because of opening the relief valve. The minimum pressure at the left end of intake cam oil bore is 4.601 bar. At 500 rpm, the relief valve is not opened. The oil pressure at pump exit is 3.426 bar at the closing state of the relief valve. The pressure at the rear end of intake cam oil bore is 3.230 bar.

e) With new and current oil pump, the suction speeds at every rpm are reasonable to most of engine speeds as comparing to the recommended speed. The centrifugal resistant pressure dose not prevents the inlet oil at the entrance of crankshaft oil bore. Also the saturation pressure for the entrained air bubble, in which the supposed maximum air volume in oil at rated speed is about 3%, is lower enough comparing to the minimum pressures of crank shaft oil bores.

References

1. Lo, R. S., "Digital Simulation of Engine Lubrication Systems," *SAE 710205*, 1971.
2. Heubner, K. H., "A Simplified Approach to Flow Network Analysis: Application to Engine Lubrication Systems," *SAE 750080*, 1975.
3. Ricardo Consulting Engineers, Lubricating Oil Systems for Automotive Engines, Design Proposal - DP76/155, March 1976.
4. Neu, E. A., Wade, J. A., and Chu, A. C., "Simulating the Lubrication System of a Diesel Engine," *SAE 770032*, 1977.
5. Kluck, C. E., Olsen, P. W., and Skriba, S. W., "Lubrication System Design Considerations for Heavy-Duty Diesel Engines," *SAE 861224*, 1986.
6. Tran, P., Yamamoto, T., Baba, Y., and Hoshi, M., " An Analysis of Lubricating System of Automobile Gasoline Engine," *SAE 871659*, 1987.
7. Hass, A., Esch, T., Fahl, E., Kreuter, P., and Pischinger, F., "Optimized Design of the Lubrication System of Modern Combustion Engines," *SAE 912407*, 1991.
8. Mian, M. A., "Design and Analysis of Engine Lubrication System," *SAE 970637*, pp. 219-232, 1997.
9. Chun, S. M., "Network Analysis of an Engine Lubrication System," *Tribology International*, Vol. 36, No.8, pp. 607-617, 2003.
10. M. Chun, Y. W. Park, and S. Jang, "A Study on Effects of Oil Aeration Level on Engine Lubrication System by Using Computer Program," *J. of The KSTLE*, Vol. 17, No. 3, pp. 198-208, 2001.
11. Chun, S. M., "The calculation of Engine Bearing Journal Orbit Using Mobility Method," *Automotive Technology and News, Daewoo Motor Co., Ltd.*, Vol. 34, No. 3, pp. 4-15, 1991.